

Accelerated recovery of calcium carbonate production in coral reefs using low-tech ecological restoration

J.J. Adolfo Tortolero-Langarica^{a,*}, Alma P. Rodríguez-Troncoso^b, Amílcar L. Cupul-Magaña^b, Lucy C. Alarcón-Ortega^c, Jeimy D. Santiago-Valentín^b

^a Instituto Tecnológico de Bahía de Banderas, Tecnológico Nacional de México, Crucero a Punta de Mita S/N, Bahía de Banderas C.P. 63734, Nayarit, Mexico

^b Laboratorio de Ecología Marina, Centro de Investigaciones Costeras, Centro Universitario de la Costa, Universidad de Guadalajara, Avenida Universidad No. 203, Puerto Vallarta CP 48280, Jalisco, Mexico

^c Instituto de Ciencias del Mar y Limnología, Universidad Nacional Autónoma de México (Unidad Académica Mazatlán), Av. Joel Montes Camarena s/n, Mazatlán C.P. 82040, Sinaloa, Mexico

ARTICLE INFO

Keywords:

Coral restoration
Coral growth
Eastern tropical Pacific
Branching corals
Carbonate budgets

ABSTRACT

Ongoing climate change and frequent anomalous thermal events have greatly contributed to the deterioration of coral reefs worldwide, exacerbating declines in coral reef formation and ecosystem service provision. Under this climate change scenario, the development and improvement of restoration techniques will be required to cope with coral reef degradation. This study demonstrates the potential use of direct relocation of coral of opportunity as an effective long-term ecological restoration tool. We assessed coral growth parameters (cm yr^{-1}), attachment rate (%), ecological volume ($\text{cm}^3 \text{yr}^{-1}$), including long-term evaluation of annual live coral cover (%) and calcium carbonate production ($\text{kg CaCO}_3 \text{m}^{-2} \text{yr}^{-1}$) during 5-years (2013–2018) using resilient branching coral *Pocillopora* spp. The results show a survivorship of 67%, high self-attachment (100%) during the first 6-months, and size augmentation of $\sim 167\%$ in growth parameters ($2.94\text{--}4.47 \text{ cm yr}^{-1}$) and $\sim 418\%$ in ecological volume. Over the long-term, live coral cover increased from 13 to 28% (+4% per year) with an accumulated carbonate production of $14.53 \text{ kg CaCO}_3 \text{m}^{-2}$ ($\sim 3 \text{ kg CaCO}_3 \text{m}^{-2} \text{yr}^{-1}$) resulting from the restoration process, and we found evidence for high resistance and recovery after periods of thermal anomalies. The data validate the use of direct propagation of corals of opportunity as a one of the most feasible and practical techniques to long-term restoration of damaged and degraded coral reef areas, which may help in their structural rehabilitation, improving coral communities and biodiversity maintenance.

1. Introduction

Hermatypic corals build the structural foundation and create complexity of coral reef communities, which supports high biodiversity and ecological processes (Sheppard et al., 2009), including ecosystem services and human livelihoods (Wilkinson, 2004; Pandolfi et al., 2011). In the last decades, coral reefs have been severely affected by anthropogenic and natural disturbances, jeopardizing their long-term maintenance (Kleypas et al., 1999; Hoegh-Guldberg et al., 2007; Bruno and Selig, 2007). Several threats are related to climate change including anomalous events of thermal stress such as El Niño South-Oscillation (ENSO), which may disrupt the symbiotic relationship between coral and food-provider endosymbiont resulting in coral bleaching, ultimately threatening coral survival (Hoegh-Guldberg, 1999). Intense and

more frequent ENSO events in synergy with local stressors such as overfishing, nutrient loading, pollution, overexploitation and coastal development, disrupt coral physiological processes such as calcification, growth, reproduction and survivorship, causing coral reef degradation worldwide (Hoegh-Guldberg et al., 2007; Baker et al., 2008; Eakin et al., 2016; Hughes et al., 2018). In response to these effects on coral reefs, management actions lead by scientists, public and governmental agencies, and non-governmental organizations have established permanent restoration programs that contributes to mitigate local and global impacts, by using and developing active restoration techniques that promotes the maintenances of coral reef ecosystems (Rinkevich, 2008).

Most effective coral restoration techniques use sexual and asexual recruits of branching corals (e.g., *Acropora*, *Pocillopora*, *Montipera*,

* Corresponding author at: Laboratorio Zoología Marina, Instituto Tecnológico de Bahía de Banderas, Tecnológico Nacional de México, Crucero a Punta de Mita S/N, Bahía de Banderas C.P. 63734, Nayarit, Mexico.

E-mail addresses: adolfo.tl@bahia.tecnm.mx, adolfortortolero@hotmail.com (J.J.A. Tortolero-Langarica).

<https://doi.org/10.1016/j.ecoleng.2019.01.002>

Received 18 September 2018; Received in revised form 30 December 2018; Accepted 5 January 2019

Available online 12 January 2019

0925-8574/ © 2019 Elsevier B.V. All rights reserved.

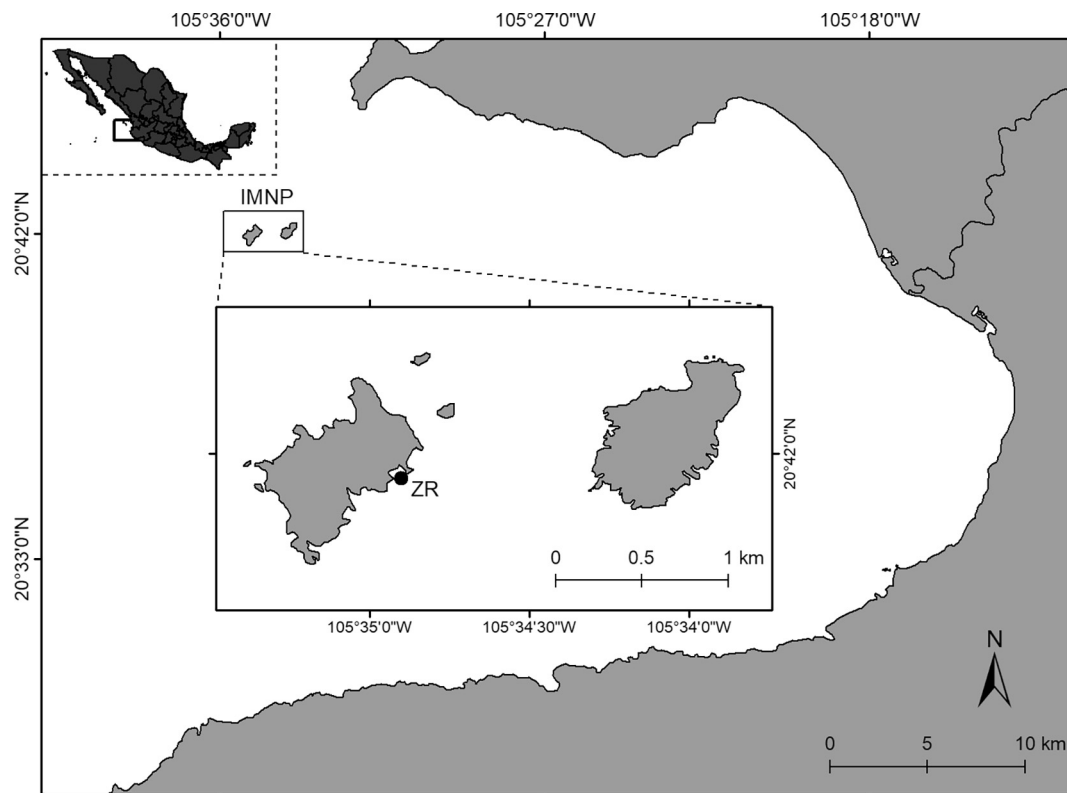


Fig. 1. Study map of the Islas Marietas National Park (IMNP). Black circle symbol denotes the Zona de restauración site (ZR).

Millepora) which are considered to be highly resistance and fast growing species in order to maximize coral propagation and rapid recovery. These restoration methods have focused on coral transplantation using coral gardening (Rinkevich, 2000, 2008, 2014; Shaish et al., 2008; Levy et al., 2010; Mbiye et al., 2010); transplantation in natural and artificial substrates (Yap et al., 1998; Clark and Edwards, 1995; Precht et al., 2002; Edwards and Gomez, 2007; Edwards, 2010; Gomez et al., 2011); *in situ* and *ex situ* coral farming (Heyward et al., 2002; Omori et al., 2003; Hatta et al., 2004; Boch and Morse, 2012) and direct propagation (Bowden-Kerby, 2001; Tortolero-Langarica et al., 2014; Nava and Figueroa-Camacho, 2017). However, most restoration programs monitor growth and survival over short timescales (~1 year), which would be considered an important indicator only as an initial evaluation (Guest et al., 2011; Gomez et al., 2014). Longer-term, continuous monitoring must be conducted to ensure self-suitability of coral restoration, that allows the establishment of potential management and conservation strategies over long timescales (Sale, 2008; Gomez et al., 2014; Suding et al., 2015; Montero-Serra et al., 2017; Rodgers et al., 2017).

Assessment of long-term scale parameters such as change in live coral cover (%) defined as growth in the extension of coral colonies on the benthic substrate and ecological volume (cm^3) as well the 3-D spherical growth of coral colonies in terms of occupied volume, are important elements which contribute to long-term structural complexity and the continuous maintenance of the coral community (Alvarez-Filip et al., 2009; Shaish et al., 2010; Gomez et al., 2014). Coral cover is not only beneficial to growth and reproduction, but may also contribute to carbonate budget cycling and increase the potential accretion of CaCO_3 (e.g., calcification, carbonate production, and gross production) produced by corals and secondary calcifiers in coral reef ecosystems (Chave et al., 1972; Vecsei, 2001; Perry et al., 2008). Data on the ecological contribution of active coral reef restoration in terms of calcium carbonate production ($\text{kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$), has the potential to be used as an ecological engineering indicator in restoration studies.

The Eastern Tropical Pacific (ETP), coral communities have been affected by several thermal stress episodes of El Niño warm phase and La Niña cold phase events (1980–1982, 1997–1998, 2000–2001, 2010–2011 and 2014–2016), both of them have contributed to losses > 90% of coral coverage, affecting to reef associated biodiversity in the region (Glynn, 1984, 2000, 2001; Glynn and Ault, 2000; Jiménez et al., 2001; Carriquiry et al., 2001; Reyes-Bonilla et al., 2002; Cupul-Magaña and Calderon-Aguilera, 2008; Hughes et al., 2018). Despite the degradation of coral reef communities and their low potential for calcification (Cabral-Tena et al., 2018), efforts to increase coral recovery and develop restoration strategies have been minimal over the past in the entire ETP (Guzmán, 1991). In recent years, a few coral restoration studies have attempted to used non-destructive methods and developed restoration techniques using natural asexual fragmentation “corals of opportunity” with positive results, including high survivorship and significant growth (Tortolero-Langarica et al., 2014; Nava and Figueroa-Camacho, 2017). Nevertheless, there is not sufficient evidence of long-term (> 5 years) restoration, including information before and after environmental disturbance to determinate coral restoration viability (Liñán-Cabello et al., 2010; Tortolero-Langarica et al., 2014; Tortolero-Langarica et al., 2017; Nava and Figueroa-Camacho, 2017; Muñiz-Anguiano et al., 2017). Therefore, the present study evaluates the long-term effectiveness of restoration technique based on natural remediation processes (i.e., asexual recruitment), using direct propagation of the coral *Pocillopora* spp. to (a) recognize the effect of long-term restoration on live coral cover and calcium carbonate production, (b) determine the increment of monthly and annual growth parameters and ecological volume, and (c) evaluate the survivorship and attachment success using low-tech natural restoration strategies on damaged coral reef communities. The information allows identification of the viability and the efficiency of long-term coral restoration programs, and the benefits that coral reef support over the time in order to provide a potential management strategy in an era of rapid climate change.

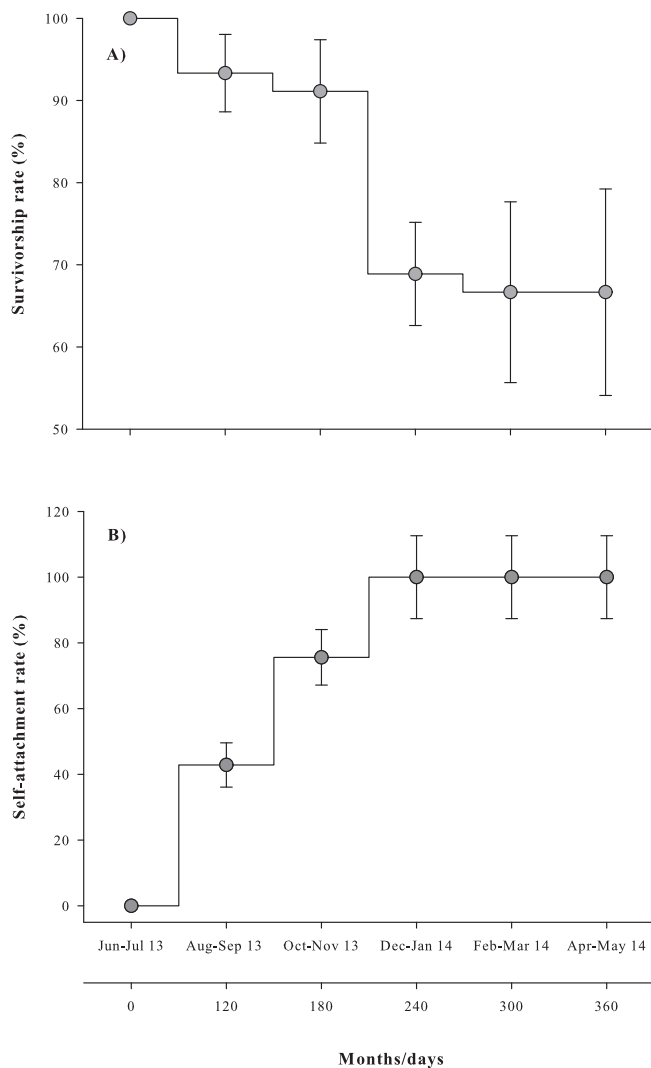


Fig. 2. Survival and coral attachment (% $\pm$ SD) during the first year of restoration. A) Survivorship rate and, B) Self-attachment rate.

2. Materials and methods

2.1. Study site

A restoration program was conducted from June 2013 to June 2018 in Islas Marietas National Park (IMNP) located 7.9 km from Nayarit, Central Mexican Pacific (CMP) (Fig. 1). The IMNP is an insular zone composed of two volcanic islands which contain many fringing and isolated patch reefs dominated by *Pocillopora* branched corals in shallow waters (3–10 m) and *Porites* and *Pavona* massive species in deeper waters (11–20 m) (CONANP, 2007). This restoration site (Zona de Restauración, Fig. 1) is a natural coral nursery whose main reproduction mode is via asexual recruits (Carpizo-ituarte et al., 2011; Santiago-Valentín and Rodríguez-Troncoso, 2016). This is a result of hydrodynamic conditions, including high wave exposure and bioerosion activity which together produce constant natural fragmentation and high abundance of corals of opportunity (Tortolero-Langarica et al., 2014). This area is influenced by two intra-annual transitional currents, the California Current and the Costa Rica Coastal Current, whose derived a high seasonal variability of seawater temperature ($> 10^{\circ}\text{C}$) (Kessler, 2006; Palacios-Hernández et al., 2010; Pantoja et al., 2012; Tortolero-Langarica et al., 2017). The area is also influenced by inter-annual thermal anomalies caused by El Niño and La Niña conditions, which may negatively affect the growth and development coral reef

communities in the area (Carriquiry et al., 2001; Reyes-Bonilla et al., 2002; Tortolero-Langarica et al., 2017).

2.2. Coral restoration parameters

A total of 127 coral fragments of *Pocillopora* species ~ 4 to 10 cm long were hand collected in Zona de Restauración (Fig. 1) at 3 m depth. All fragments were visually evaluated and those with evidence of disease, dead tissue, bleaching, sponge, and turf cover were discarded. Each fragment was re-attached within the same site of collection using plastic tie wraps (Tortolero-Langarica et al., 2014), fixed on a natural substrate (between cavities of coral matrix or rock) along two linear transects of 25 m at 3–5 m depth. From the total samples, 45 coral fragments were tagged and three-dimensional (3-D) growth increase was measured every two months during one year period; using calipers (0.05 mm precision). Maximum height growth (h) was defined as the linear distances from the bottom to the top of the colony. Maximum length growth (l) was determined as the longest diameter of the coral specimen, and width growth (w) derived from the adjacent diameter perpendicular to the length growth. The 3-D growth data were used to calculate the increase on coral structural volume of coral colonies referred in this study as “ecological volume”, $EV = \pi r^2 h$, where r = radius ($l + w / 4$) (Rinkevich and Loya, 1983; Mbije et al., 2010). Survivorship (%) was considered as the monthly percentage of living fragments without dead bleached tissue or signs of breakage. All fragments which self-adhered to the substrate were recorded as attachment rate (%) over the experiment period. Sea Water Temperature (SWT) was measured *in situ* every 25 min during the study using HOBO® (Pendant) temperature loggers installed at the study site. Daily data were pooled into monthly and annual SWT averages in order to relate temperature with monthly and annual coral growth.

2.3. Calcium carbonate production

Underwater surveys were conducted annually from 2013 to 2018, using two linear transects of 25 m $\times$ 1 m (each) to determinate annual coral cover produced by the restoration process. Percentage of the live coral cover was recorded using six replicates 1 m² quadrats along the same permanent transects used for the restoration experiment. Census-based method was employed to estimate calcium carbonate production ($\text{kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1} = \text{g cm}^{-2} \text{ yr}^{-1} \times \% \text{ coral cover}$) (Vecsei, 2004; Norzagaray-López et al., 2014). We used data on annual calcification rates ($\text{g cm}^{-2} \text{ yr}^{-1}$) previously reported for the same site and species by Tortolero-Langarica et al., 2017, and the annual live coral cover (% yr^{-1}) from this study.

Means of growth parameters, ecological volume and annual carbonate production ($\pm$ SD) were calculated. After the evaluation of normality and homoscedasticity, parametric Analysis of Variance (ANOVA) was used to compare monthly growth in height. Also, ANOVA on ranks (Kruskal-Wallis) was employed for monthly growth comparisons in length, radial and ecological volume. Annual differences in coral cover and carbonate production were also tested using Kruskal-Wallis, and a Tukey test was used for all pairwise comparisons ($p < 0.005$). Linear regression (r) was used to the determinate relationship between growth parameters and SWT at a month and year level. Statistical analyses were performed by Sigma Plot 11.0 (Systat Software, Inc), using interval confidence of 95% ($\alpha = 0.05$) to determine significance difference

3. Results

Survivorship of coral fragments during the first year was of 67% (Fig. 2). Mortality was 32%, most related to missing fragments by detachment (20%), but also associated with coral bleaching (12%) and subsequent algae overgrowth observed during January 2014. Coral survival after 5-years of restoration was of 51% Attachment

Table 1

Mean coral growth parameters ($\pm$ SD) of *Pocillopora* corals at two-month and annual intervals. H = height, W = width, L = length, EV = ecological volume, Cover = live coral cover, CCP = calcium carbonate production and SWT = seawater temperature.

Month	Day	Growth parameter					Year	Annual parameters			
		H (cm)	W (cm)	L (cm)	EV (cm ³)	SWT (°C)		Cover (%)	CCP (kg CaCO ₃ m ⁻² yr ⁻¹)	SWT (°C)	
Jun–Jul 2013	0	7.81 $\pm$ 1.71	5.62 $\pm$ 1.77	4.29 $\pm$ 1.43	143.86 $\pm$ 66.87	28.15 $\pm$ 1.52	2013	13.08 $\pm$ 4.12	7.78 $\pm$ 2.15	26.92 $\pm$ 2.78	
Aug–Sep 2013	120	8.65 $\pm$ 1.64	6.05 $\pm$ 1.77	4.40 $\pm$ 1.52	190.95 $\pm$ 93.66	29.92 $\pm$ 0.46	2014	15.33 $\pm$ 0.70	9.12 $\pm$ 0.42	27.80 $\pm$ 2.81	
Oct–Nov 2013	180	9.58 $\pm$ 1.65	6.73 $\pm$ 1.97	5.29 $\pm$ 1.69	273.78 $\pm$ 129.03	29.41 $\pm$ 0.75	2015	26.16 $\pm$ 3.06	15.57 $\pm$ 1.82	28.08 $\pm$ 2.71	
Dec–Jan 2014	240	11.14 $\pm$ 1.69	7.82 $\pm$ 1.76	6.14 $\pm$ 1.37	428.37 $\pm$ 158.72	26.47 $\pm$ 0.64	2016	17.25 $\pm$ 1.77	10.26 $\pm$ 1.05	27.04 $\pm$ 2.69	
Feb–Mar 2014	300	11.63 $\pm$ 1.54	8.31 $\pm$ 1.82	6.80 $\pm$ 1.30	514.33 $\pm$ 171.59	24.54 $\pm$ 1.29	2017	26.66 $\pm$ 1.65	15.87 $\pm$ 0.98	26.56 $\pm$ 3.29	
Apr–May 2014	360	12.29 $\pm$ 1.62	9.00 $\pm$ 1.67	8.98 $\pm$ 1.20	602.41 $\pm$ 192.11	25.25 $\pm$ 2.54	2018	28.58 $\pm$ 9.07	17.01 $\pm$ 5.39	–	

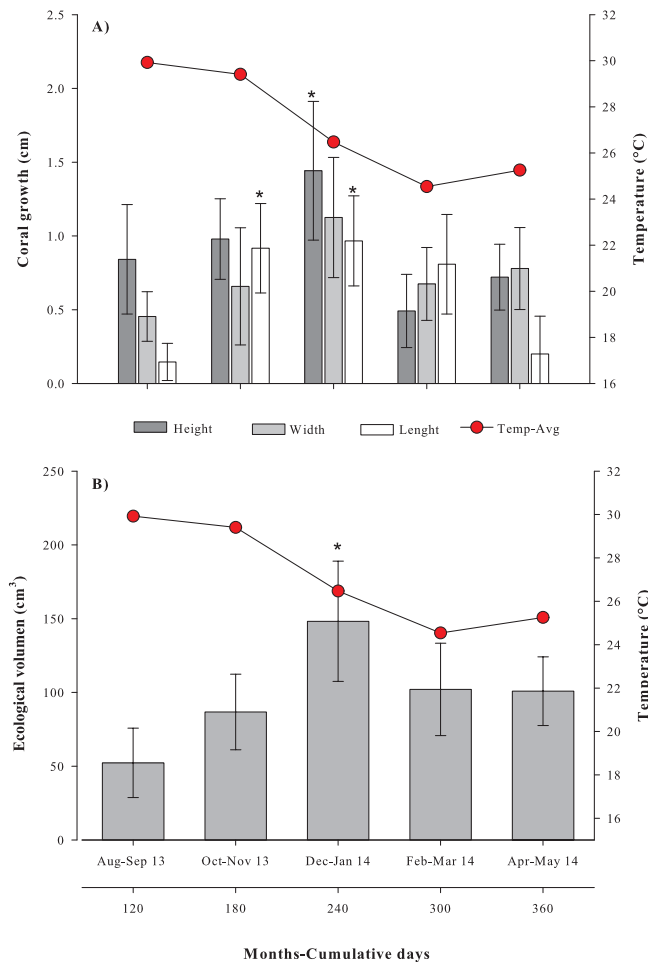


Fig. 3. Coral growth parameters of *Pocillopora* species and seawater temperature during one year of restoration. A) Bimonthly height, width and length growth (cm $\pm$ 95% confidence limits), B) Bimonthly ecological volume (cm³ $\pm$ 95% confidence limits). Stars (*) denote significant differences ($p < 0.05$) between months.

effectiveness on nature substrate was $> 50\%$ during the first four months and 100% of fragments had self-attached by six months after the initial restoration (Fig. 2).

Growth data of *Pocillopora* colonies (Table 1; Fig. 3) reveals an increase of 163.37% in height with respect to initial size with a mean ($\pm$ SD) accumulated growth of 4.47 ± 1.07 cm yr⁻¹ (ranging from 1.80 to 6.20 cm) after one year of restoration (Fig. 4). Growth in length increased 171%, with a maximum accumulated growth of 3.53 ± 1.41 cm yr⁻¹. Accumulated growth in width was 2.94 ± 1.10 cm yr⁻¹, equivalent to 176% increase (Fig. 3). Values of EV (Table 1 and Fig. 3) showed an annual increase of 418%, with mean

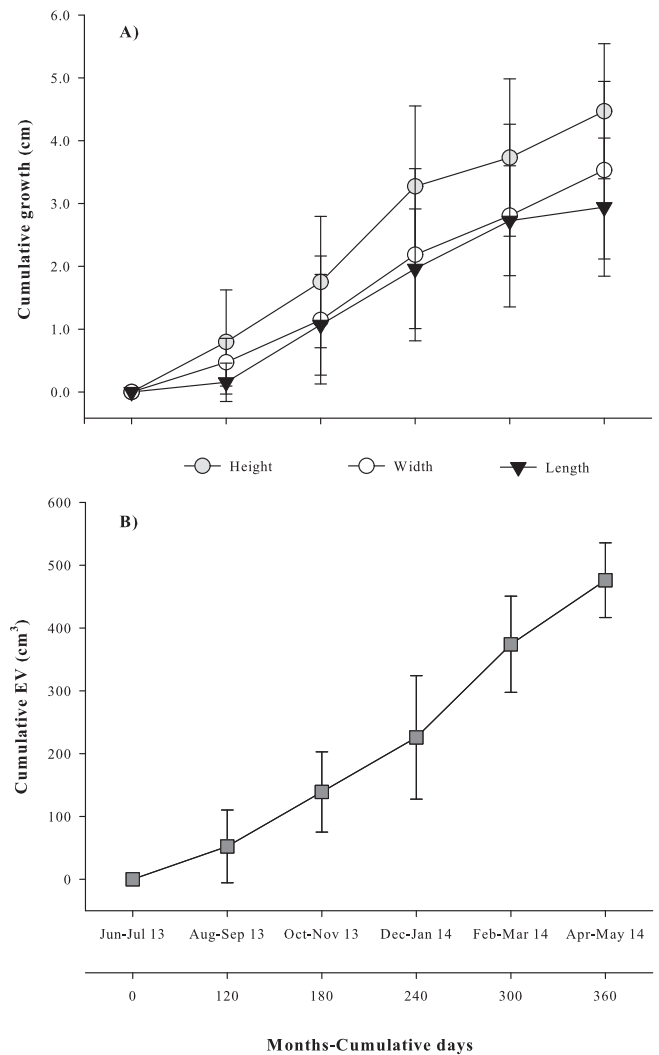


Fig. 4. Coral growth parameters ($\pm$ SD) after one year of restoration. A) Cumulative growth (cm), B) Ecological volume = EV (cm³).

accumulated volume of 476 ± 59.43 cm³ yr⁻¹ (Fig. 4). At monthly level, data exhibited mean two-month growth of 0.98 ± 0.35 cm, 0.74 ± 0.25 cm and 0.60 ± 0.40 cm for height, length and width respectively, and 98 ± 34.52 cm³ for EV growth (Fig. 3). Growth comparisons between months showed significance differences in height ($H = 21.454$, $p < 0.001$), length ($H = 33.585$, $p < 0.001$), and EV ($H = 29.394$, $p < 0.001$); *a posteriori* analyses (Tukey test) indicated that December-January having the highest mean monthly values ($p < 0.05$) in most parameters (Fig. 3 and Table 1).

Following the restoration process, live coral cover doubled over the

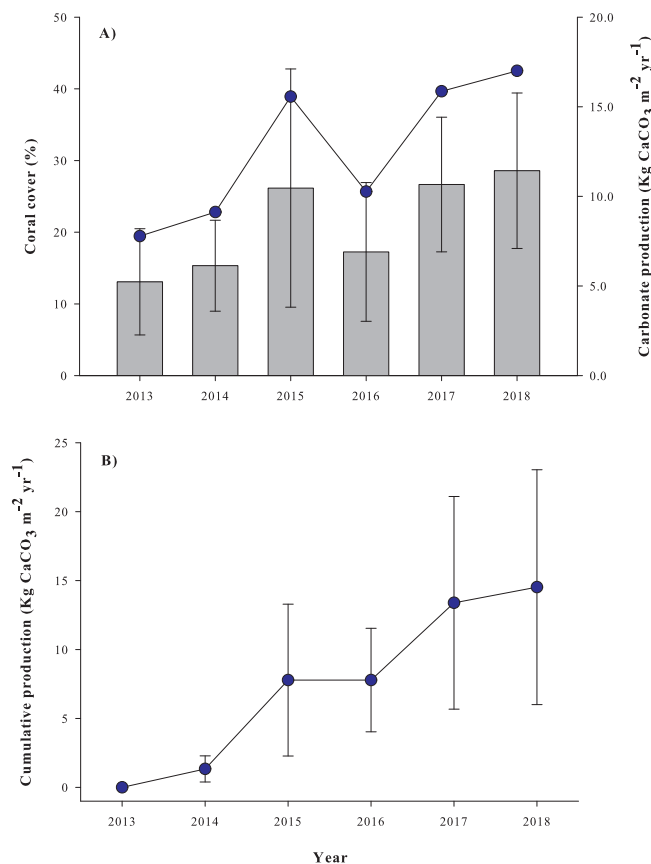


Fig. 5. Long-term restoration effects on coral parameters during 2013–2018. A) Mean annual live coral cover (% $\pm$ 95% confidence limits) and mean calcium carbonate production, B) Cumulative calcium carbonate production (mean $\pm$ SD).

subsequent five years (Fig. 5 and Table 1) with a mean of 4.88% increase per year. During the first years, coral cover increased from 13% in 2013 to 26% in 2015, with a noticeable decrease of up to 17% during bleaching episode between 2015 and 2016. However, in the following two years (2017–2018) coral cover showed a high recovery back to 28% (Fig. 5). Calcium carbonate production showed an increase of 218% after five years, with a mean carbonate production of $12.60 \pm 3.99 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ (ranging from 7.78 to $17.01 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$) across the 5-years of monitoring (Fig. 5). Data reveals a mean carbonate production of $2.91 \pm 2.78 \text{ kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ produced by the restored corals and accumulated carbonate production of $14.52 \pm 5.27 \text{ kg CaCO}_3 \text{ m}^{-2}$ (Table 1; Fig. 5). However, comparisons between years resulted non-significant in both coral cover and carbonate production ($p = 0.075$).

Annual mean SWT was ($26.36 \pm 5.04^\circ \text{C}$) during the restoration process, with a noticeable difference between the cold season ($22.26 \pm 2.37^\circ \text{C}$ January–May) and the warm water season ($29.54 \pm 1.28^\circ \text{C}$ June–November). The warmest year was 2015 with a mean SWT of 28.75°C . Annual SWT difference ($H = 21.431$, $p < 0.001$) was associated with the warmer seasons during 2014 and 2015 (Table 1). The relationship between coral bimonthly growth parameters and SWT during the experiment period, as well as between annual SWT and calcium carbonate production were both non-significant ($p > 0.05$).

4. Discussion

The development and implementation of active restoration techniques and conservation options are required to rehabilitate and maintain coral reef ecosystem worldwide (Bowden-Kerby, 2001; Rinkevich,

2014). Many restoration techniques have been shown to be successful and popular, but they are limited to particular environmental conditions such as substrata type, sexual recruits and sheltered zones (Edwards and Gomez, 2007; Edwards, 2010; Rinkevich, 2014). However, the rough hydrodynamic conditions and lack of synchrony in sexual reproduction in the CMP (Kessler, 2006; Carpizo-Ituarte et al., 2011; Santiago-Valentín et al., 2018), makes many common restoration techniques (i.e., coral gardening, farming and artificial substrates) unfeasible. Despite these particular conditions, an alternative successful option emerged here was the direct relocation of corals of opportunity as a fast and low-tech coral restoration (Fig. 6). The re-attachment of healthy coral fragments on natural substrata facilitates the practical installation of many potential new coral colonies instantly without extra protocols to consider (i.e., pre-acclimation, gardening, transportation) (Tortolero-Langarica et al., 2014).

This non-destructive method used fast-growth coral species and natural asexual recruits of branching corals such as *Pocillopora* spp. to restore coral cover successfully over longer-term periods than previously measured (Gomez et al., 2014; Tortolero-Langarica et al., 2014). The availability of many ramets from original genets whose life histories allow independently growth after natural fragmentation gives the opportunity to regenerate coral population naturally (Highsmith, 1982; Rinkevich, 2005). This natural strategy is used here to accelerate coral reef recovery via restoration, and consequently enhance coral cover, carbonate production rate and the continuous 3-D structural complexity of coral reef ecosystems.

The results of this study show similar survivorship ($> 60\%$) and mortality rates after one year of restoration when compared to different transplantation techniques such as *in situ* and *ex situ* coral gardening, transplantation in natural and artificial restoration (Fig. 2) (Edwards and Gomez, 2007; Edwards, 2010; Shaish et al., 2010; Mbije et al., 2010; Liñán-Cabello et al., 2010; Gomez et al., 2011; Boch and Morse, 2012; Tortolero-Langarica et al., 2014; Muñoz-Anguiano et al., 2017; Nava and Figueroa-Camacho, 2017). However, is important to emphasize that direct propagation technique using in this study also showed higher survivorship at long-term (5 years) compared with transplantation methods (Rodgers et al., 2017). Including the high attachment rates of 100% during the first six months (Fig. 2), which reveals the efficiency of the use of tie wraps to bind coral fragments to natural substrate as a potentially one of the most practical restoration techniques (Rinkevich, 2005; Mbije et al., 2010; Forrester et al., 2011; Boch and Morse, 2012; Nava and Figueroa-Camacho, 2017). This simple method using fragments 5–10 cm in length demonstrated here also has the advantage of not needing a pre-acclimation stage (nursery phase) or extra consideration prior the transplantation, which may reduce cost of installation and maintenance (Omori et al., 2003; Edwards and Gomez, 2007; Shaish et al., 2010). The direct outplanting of asexual recruits also showed fast acclimation to the environment with a low mortality rate even during periods of anomalous high SWT (Fig. 3).

The coral growth of *Pocillopora* spp. showed an almost doubling compared to the initial size in height, large and width growth (Fig. 3). These findings are similar to other studies and corroborate that Pocilloporid corals showed the highest growth rate reported for the entire ETP region (Guzmán, 1991; Guzmán and Cortés, 1989; Jiménez and Cortés, 2003; Dullo, 2005; Manzello, 2010; Tortolero-Langarica et al., 2014; Medellín-Maldonado et al., 2016; Tortolero-Langarica et al., 2017; Muñoz-Anguiano et al., 2017; Nava and Figueroa-Camacho, 2017). This result is also demonstrated by monthly growth data (Fig. 3 and Table 1), as the highest values in the northeast tropical Pacific area with a constant increment of $> 0.8 \text{ cm mo}^{-1}$ (Tortolero-Langarica et al., 2014, 2017; Medellín-Maldonado et al., 2016; Muñoz-Anguiano et al., 2017; Nava and Figueroa-Camacho, 2017). This may be influenced by the ability of *Pocillopora* spp. and their endosymbiont to acclimate and inhabit at a different temperature, light irradiance, nutrient load and pH regimes, in order to modulate their energy budget available for physiological processes (LaJeunesse et al., 2010; Manzello,

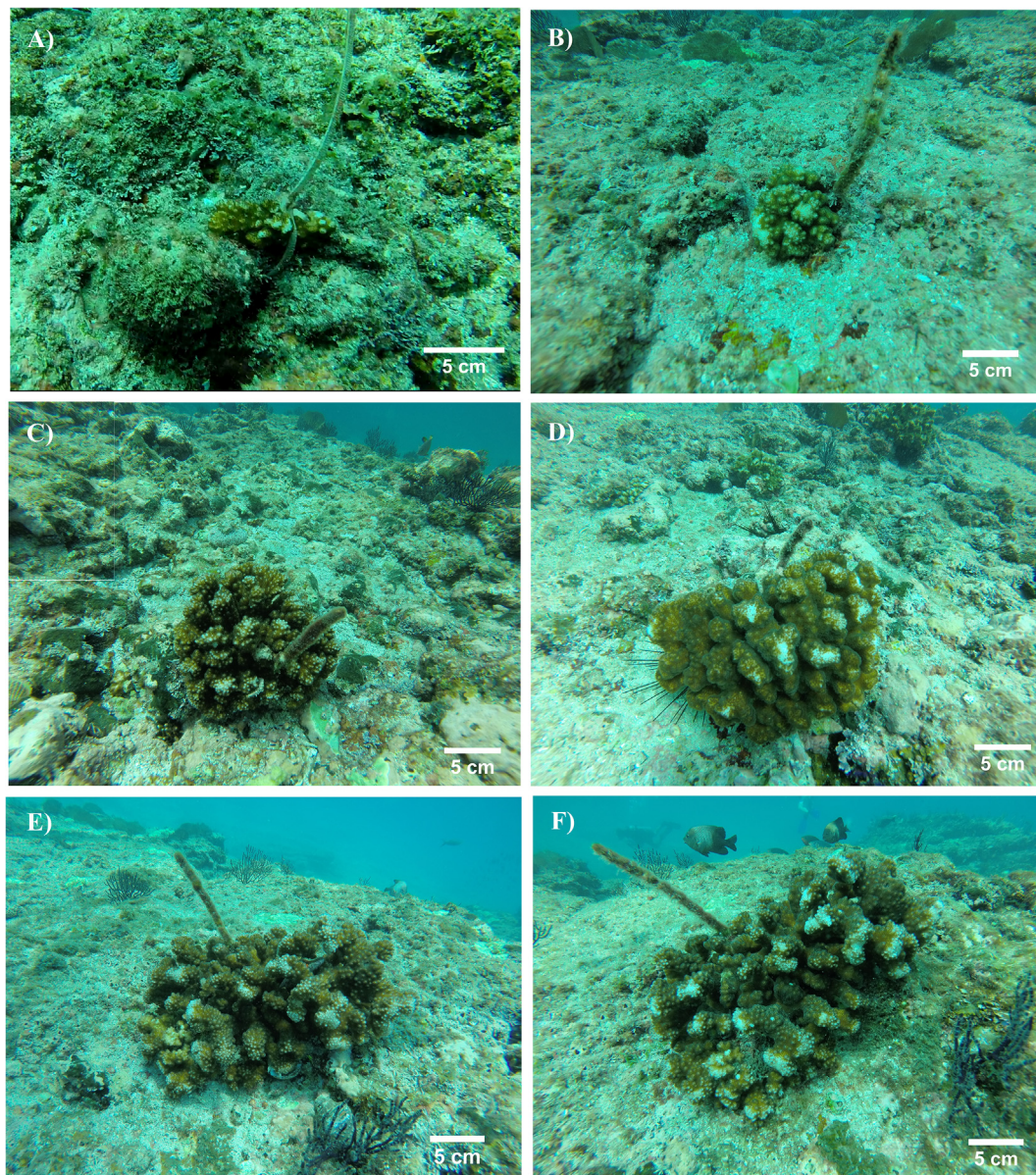


Fig. 6. Annual growth sequence from 2013 to 2018 of restored *Pocillopora* spp. corals, using direct propagation technique on natural substrata. A) initial coral fragment (2013), B) first annual period (2014), C) second annual period (2015), D) third annual period (2016), E) fourth annual period (2017), and F) final coral growth (2018).

2010; Manzello et al., 2017; Tortolero-Langarica et al., 2017). The high thermo-tolerance of *Symbiodinium* algae (Clade-D), who may cope with high and low SWT regimes and help the coral host to persist through anomalous events as ENSO episodes (Glynn, 2001; LaJeunesse et al., 2010; Rodríguez-Troncoso et al., 2010; Tortolero-Langarica et al., 2017). The high resilience capacity of the *Pocillopora* genera may promote population maintenance via restoration even in suboptimal conditions (Glynn et al., 2017).

Restoration not only benefits individual coral growth but also enhances topographical reef complexity, which may be evident through measures of ecological volume. The EV results herein exhibit sub-spherical 3-D structural changes of *Pocillopora* colonies, increasing four orders of magnitude during a single year period (Fig. 4; Table 1). The excellent performance and plasticity of *Pocillopora* species to develop complex structures over long-time scales is similar to other branching species (Shaish et al., 2010; Mbije et al., 2010; Boch and Morse, 2012; Paz-García et al., 2015). Our data on monthly EV exhibited an high increment $\sim 100 \text{ cm}^3$ during optimal conditions ($26\text{--}29^\circ\text{C}$) of SWT, and

a slight negative tendency during extreme temperatures ($> 31^\circ\text{C}$) (Fig. 4). This pattern is also reflected in monthly growth values (Fig. 3; Table 1), where growth rate was reduced due to the influence of thermal anomalies during the warmest months, with high recovery in growth parameters within subsequent months. This is a particular growth model reported for *Pocillopora* spp. with a positive physiological response of the species that allows them to recover after SWT anomalies (Tortolero-Langarica et al., 2017). Hence, the coral restoration technique used in this study had beneficial results for the 3-D reconstruction of the coral reef (growth and EV), and provides a critical advancement in coral restoration studies. We, demonstrate the capability to augment and restore topographical rugosity, which is an important element of the functionality of coral reef ecosystems in supporting biodiversity and providing ecosystem service such as shoreline protection (Sheppard et al., 2009; Alvarez-Filip et al., 2009).

The significant two-fold increase of live coral cover promoted by restoration in this study (Fig. 6) before and after thermal anomalies, revealed the excellent performance of corals such as *Pocillopora* to

spread over the benthic substrate (+4% per year). This coral cover augment is not only essential to the reef cementation, but may also increase the potential of local long-term production of sexual and asexual recruitment (Montoya-Maya et al., 2016). This restoration method includes the high carbonate production promoted by Pocilloporid corals, representing the species with the highest rate (+12 kg CaCO₃ m⁻² yr⁻¹) at genera level in the ETP (Vecsei, 2001, 2004; Halfar et al., 2005; Norzagaray-López et al., 2014). These species are also responsible for > 90% of the total coral community production in the region (Cabral-Tena et al., 2018). Over multi-year time scales, restored corals in our study provided a significant contribution in calcium carbonate production (14.52 kg CaCO₃ m⁻², after five years of coral restoration) in spite an intense ENSO event in 2015–2016 (Fig. 6). This is an encouraging result in the context of the projected future losses in carbonate budgets (85%) and coral growth (0.9% yr⁻¹) from models for the ETP (Manzello, 2010; Cabral-Tena et al., 2018). At this point, branching corals as *Pocillopora* spp. are one of the most amenable species in terms of coral cover and CaCO₃ production for use in long-term coral reef rehabilitation and the maintenance of primary CaCO₃ structure in the ETP (Vecsei, 2004; Tortolero-Langarica et al., 2014; Cabral-Tena et al., 2018).

While this study provides some hope for coral recovery using active remediation actions, it is important that managers and conservation practitioners continue to evaluate coral growth parameters. But also consider the additional biochemical process as erosion and dissolutions rates (net accretion), as well as local stressors impacts, in order to fully understand long-term conservation and restoration strategies of coral reef ecosystems.

5. Conclusions

The results of this study highlight the strong potential for direct propagation of corals of opportunity for long-term ecological restoration of damaged and degraded coral reef areas (Tortolero-Langarica et al., 2014). The technique resulted in fast coral growth, extensive coral cover and high carbonate production over short and long-term periods. At this point, we recommend the implementation of remediation techniques that includes long-term monitoring of parameters such as EV, coral cover and carbonate production rates in order to establish reliable and effective restoration programs. Ultimately, rehabilitation of coral reef areas through active restoration techniques may improve biodiversity and coral community recovery, which will, in turn revive environmental and economic services that healthy coral reefs provide.

Acknowledgements

The authors give thanks to the authorities of Islas Marietas National Park (SEMARNAT/CONANP) and the organization Protección y Restauración de Islas y Zonas Naturales AC (PROZONA) for their assistance with field operations. The authors would like to thank Jennifer Caselle for valuable comments on the manuscript's English and scientific content.

Funding

The present work was supported by the PRODEP project 220265 to APRT and the project P/PIFI-2010-14MSU0010Z-10 to ACM. Also supported by SEMARNAT/CONANP [Grant Numbers: PROCER/CCER/DROPC/09/2016, CONANP/PROMANP/MB/24/2017 and PROCER/CER/119/2018]. The entities had no role in study design, analysis and interpretation of data, decision to publish, or preparation of the manuscript.

Author contributions

JJTL, APRT and ALCM conceived of the experiment, JJTL, APRT,

JDSV, LCAO conducted the experiment. JJTL analyzed the results, JJTL wrote the manuscript. All authors reviewed and edited the manuscript.

Competing financial interests

The authors declare no competing financial interests.

References

- Alvarez-Filip, L., Dulvy, N.K., Gill, J.A., Côté, I.M., Watkinson, A.R., 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proc. R. Soc. Lond. B Biol. Sci.* 276, 3019–3025. <https://doi.org/10.1098/rspb.2009.0339>.
- Baker, A.C., Glynn, P.W., Riegl, B., 2008. Climate change and coral reef bleaching: an ecological assessment of long-term impacts, recovery trends, and future outlook. *Estuar. Coast. Shelf Sci.* 80, 435–471. <https://doi.org/10.1016/j.ecss.2008.09.003>.
- Boch, C.A., Morse, A.N.C., 2012. Testing the effectiveness of direct propagation techniques for coral restoration of *Acropora* spp. *Ecol. Eng.* 40, 11–17. <https://doi.org/10.1016/j.ecoleng.2011.12.026>.
- Bowden-Kerby, A., 2001. Low tech coral reef restoration methods modeled after natural fragmentation process. *Bull. Mar. Sci.* 69, 915–931.
- Bruno, J.F., Selig, E.R., 2007. Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. *PLoS One* 8, 711. <https://doi.org/10.1371/journal.pone.0000711>.
- Cabral-Tena, R.A., López-Pérez, A., Reyes-Bonilla, H., Calderon-Aguilera, L.E., Norzagaray-López, C.O., Rodríguez-Zaragoza, F.A., Cupul-Magaña, A., Rodríguez-Troncoso, A.P., Ayala-Bocos, A., 2018. Calcification of coral assemblages in the eastern Pacific: Reshuffling calcification scenarios under climate change. *Ecol. Indicators* 95, 726–734. <https://doi.org/10.1016/j.ecolind.2018.08.021>.
- Carpizo-Ituarte, E., Vizcaíno-Ochoa, V., Chi-Barragán, G., Tapia-Vázquez, O., Cupul-Magaña, A.L., Medina-Rosas, P., 2011. Evidence of sexual reproduction in the hermaphroditic corals *Pocillopora damicornis*, *Porites panamensis*, and *Pavona gigantea* in Banderas Bay, Mexican Pacific. *Cienc. Mar.* 37, 97–112. <https://doi.org/10.7773/cm.v37i1.1773>.
- Carriquiry, J.D., Cupul-Magaña, A.L., Rodríguez-Zaragoza, F., Medina-Rosas, P., 2001. Coral bleaching and mortality in the Mexican Pacific during the 1997–98 El Niño, and prediction from a remote sensing approach. *Bull. Mar. Sci.* 69, 237–249.
- Chave, K.E., Smith, S.V., Roy, K.J., 1972. Carbonate production by coral reefs. *Mar. Geol.* 12, 123–140. [https://doi.org/10.1016/0025-3227\(72\)90024-2](https://doi.org/10.1016/0025-3227(72)90024-2).
- Clark, S., Edwards, A.J., 1995. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldive Islands. *Coral Reefs* 14, 201–213. <https://doi.org/10.1007/BF00334342>.
- CONANP, 2007. In: Programa de Conservación y Manejo del Parque Nacional Islas Marietas. Comisión Nacional de Áreas Naturales Protegidas, pp. 155 ISBN 978-968-817-851-5.
- Cupul-Magaña, A., Calderon-Aguilera, L., 2008. Cold water bleaching at Islas Marietas National Park, Nayarit, México. In: 15vo Congreso Nacional de Oceanografía, Veracruz, México.
- Dullo, W.C., 2005. Coral growth and reef growth: a brief review. *Facies* 51, 33–48. <https://doi.org/10.1007/s10347-005-0060-y>.
- Eakin, C.M., Liu, G., De La Cour, J.L., Heron, S.F., Skirving, W.J., Geiger, E.F., Tirak, K.V., Strong, A.M., 2016. Global coral bleaching 2014–2017. *Reef Encounter* 31, 20–26.
- Edwards, A.J., Gomez, E.D., 2007. Reef restoration concepts and guidelines: making sensible management choices in the face of uncertainty. In: St. Lucia, Australia: Coral Reef Targeted Research and Capacity Building for Management Program.
- Edwards, A.J., 2010. In: Reef Rehabilitation Manual. The Coral Reef Targeted Research and capacity building for management program, Queensland, Australia, pp. 166.
- Forrester, G.E., O'Connell-Rodwell, C., Bailly, P., Forrester, L.M., Giovannini, S., Harmon, L., Karis, R., Krumholz, J., Rodwell, T., Jarecki, L., 2011. Evaluating methods for transplanting endangered elkhorn corals in the Virgin Islands. *Restor. Ecol.* 19, 299–306. <https://doi.org/10.1111/j.1526-100X.2010.00664.x>.
- Glynn, P.W., 1984. Widespread coral mortality and the 1982–83 El Niño Warming Events. *Environ. Conserv.* 11, 133–146. <https://doi.org/10.1017/S0376892900013825>.
- Glynn, P.W., 2000. Effects of the 1997–98 El Niño Southern-oscillation on Eastern Pacific corals and coral reefs: An overview. In: Proc. 9th Int. Coral Reefs Symp. Bali, Indonesia. 2, pp. 1169–1174.
- Glynn, P.W., 2001. Eastern Pacific coral reef ecosystems. In: In: Seeliger, U., Kjerfve, B. (Eds.), Coastal Marine Ecosystems of Latin America 144. Springer-Verlag Berlin Heidelberg. *Ecol. Stud.*, pp. 281–305.
- Glynn, P.W., Ault, P.S., 2000. A biogeographic analysis and review of the far eastern Pacific Coral Reef region. *Coral Reefs* 19, 1–23. <https://doi.org/10.1007/s003380050220>.
- Glynn, P.W., Alvarado, J.J., Banks, S., Cortés, J., Feingold, J.S., Jiménez, C., Maragos, J.E., Martínez, P., Maté, J.J., Moanga, D.A., Navarrete, S., Reyes-Bonilla, H., Riegl, B., Rivera, F., Vargas-Ángel, B., Wieters, E.A., Zapata, F.A., 2017. Eastern Pacific coral reef provinces, coral community structure and composition: an overview. In: Glynn, P., Manzello, D.P., Enochs, I. (Eds.), Coral Reefs of the Eastern Tropical Pacific. Springer, Netherlands, pp. 107–176.
- Gomez, E.D., Yap, H.T., Cabaitan, P.C., Dizon, R.M., 2011. Successful transplantation of a fragmenting coral, *Montipora digitata* for reef rehabilitation. *Coast. Manage.* 39, 556–574. <https://doi.org/10.1080/08920753.2011.600240>.
- Gomez, E.D., Cabaitan, P.C., Yap, H.T., Dizon, R.M., 2014. Can coral cover be restored in the absence of natural recruitment and reef recovery? *Restoration Ecol.* 1–9. <https://doi.org/10.1007/s10044-014-0000-0>.

- doi.org/10.1111/rec.12041.
- Guest, J.R., Dizon, R.M., Edwards, A.J., Franco, C., Gomez, E.D., 2011. How quickly do fragments of corals “self-attach” after transplantation? *Restoration Ecol.* 19, 234–242. <https://doi.org/10.1111/j.1526-100X.2009.00562.x>.
- Guzmán, H.M., 1991. Restoration of coral reefs in Pacific Costa Rica. *Conserv. Biol.* 5, 189–195. <https://doi.org/10.1111/j.1523-1739.1991.tb00123.x>.
- Guzmán, H.M., Cortés, J., 1989. Growth rates of eight species of scleractinian corals in the eastern Pacific (Costa Rica). *Bull. Mar. Sci.* 44, 1186–1194.
- Halfar, J., Godínez-Orta, L., Rieg, B.J., Valdez-Holguin, E., Borges, J.M., 2005. Living on the edge: high-latitude *Porites* carbonate production under temperate eutrophic conditions. *Coral Reefs* 24, 582–592. <https://doi.org/10.1007/s00338-005-0029-x>.
- Hatta, M., Iwao, K., Taniguchi, H., Omori, M., 2004. Restoration technology using sexual reproduction. In: Omori, M., Fujiwara, S. (Eds.), *Manual for Restoration and Remediation of Coral Reefs*. Nature Conservation Bureau, Ministry of the Environment, Japan, pp. 14–28.
- Heyward, A.C., Smith, L.D., Rees, M., Field, S.N., 2002. Enhancement of coral recruitment by in situ mass culture of coral larvae. *Mar. Ecol. Prog. Ser.* 230, 113–118. <https://doi.org/10.3354/meps230113>.
- Highsmith, R.C., 1982. Reproduction by fragmentation in corals. *Mar. Ecol. Prog. Ser.* 7, 207–226. <https://doi.org/10.3354/meps007207>.
- Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Mar. Freshwater Res.* 50, 839–866. <https://doi.org/10.1071/MF99078>.
- Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatzioiols, M.E., 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318, 1737–1742. <https://doi.org/10.1126/science.1152509>.
- Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., Claar, D.C., Eakin, C.M., Glimour, J.P., Graham, A.J., Harison, H., Hobbs, J.A., Hoey, A.S., Hoogenboom, M., Lowe, R.J., MacCulloch, M.T., Pandolfi, J.M., Pratchett, M., Schoepf, V., Torda, G., Wilson, S.K., 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* 359, 80–83. <https://doi.org/10.1126/science.aan8048>.
- Jiménez, C., Cortés, J., León, A., Ruiz, E., 2001. Coral bleaching and mortality associated with the 1997–98 El Niño in an upwelling environment in the eastern Pacific (Gulf of Papagayo, Costa Rica). *Bull. Mar. Sci.* 68, 151–169.
- Jiménez, C., Cortés, J., 2003. Growth of seven species of scleractinian corals in an upwelling environment of the eastern Pacific (Golfo de Papagayo, Costa Rica). *Bull. Mar. Sci.* 72, 187–198.
- Kessler, W.S., 2006. The circulation of the Eastern tropical Pacific: a review. *Prog. Oceanogr.* 69, 181–217. <https://doi.org/10.1016/j.pocean.2006.03.009>.
- Kleypas, J.A., Buddemeier, R.W., Archer, D., Gattuso, J.P., Langdon, C., Opdyke, B.N., 1999. Geochemical consequences of increased carbon dioxide on coral reefs. *Science* 284, 118–120. <https://doi.org/10.1126/science.284.5411.118>.
- LaJeunesse, T.C., Smith, R., Walther, M., Pinzón, J.H., Pettay, T., McGinley, M., Aschaffenburg, M., Medina-Rosas, P., Cupul-Magaña, A.L., Perez, A.L., Reyes-Bonilla, H., Warner, M.E., 2010. Host-symbiont recombination vs. natural selection in the response of coral-dinoflagellate symbioses to environmental disturbance. *Proc. R. Soc. Lon. B.* 277, 2925–2934. <https://doi.org/10.1098/rspb.2010.0385>.
- Levy, G., Shaish, L., Haim, A., Rinkevich, B., 2010. Mid-water rope nursery-testing design and performance of a novel reef restoration instrument. *Ecol. Eng.* 36, 560–569. <https://doi.org/10.1016/j.ecoleng.2009.12.003>.
- Liñán-Cabello, M.A., Flores-Ramírez, L.A., Laurel-Sandoval, M.A., Mendoza, E., García, S., Olinda, S., Delgadillo-Nuño, M.A., 2010. Acclimation in *Pocillopora* spp. during a coral restoration program in Carrizales Bay, Colima, Mexico. *Mar. Fresh. Behav. Physiol.* 44, 1–12. <https://doi.org/10.1080/10236244.2010.537440>.
- Manzello, D.P., 2010. Coral growth with thermal stress and ocean acidification: lessons from the eastern tropical Pacific. *Coral Reefs* 29, 749–758. <https://doi.org/10.1007/s00338-010-0623-4>.
- Manzello, D.P., Eakin, C.M., Glynn, P.W., 2017. Effects of global warming and ocean acidification on carbonate budgets of eastern Pacific coral reefs. In: Glynn, P., Manzello, D.P., Enochs, I. (Eds.), *Coral Reefs of the Eastern Tropical Pacific*. Springer, Netherlands, pp. 517–533. https://doi.org/10.1007/978-94-017-7499-4_18.
- Mbije, N.E., Spanier, E., Rinkevich, B., 2010. Testing the first phase of the gardening concept as an applicable tool in restoring denuded reefs in Tanzania. *Ecol. Eng.* 36, 713–721. <https://doi.org/10.1016/j.ecoleng.2009.12.018>.
- Medellín-Maldonado, F., Cabral-Tena, R.F., López-Pérez, A., Calderón-Aguilera, L.E., Norzagaray-López, C.O., Chapa-Balcorta, C., Zepeda-Vilchis, R.C., 2016. Calcification of the main reef-building coral species on the Pacific coast of southern Mexico. *Cienc. Mar.* 42, 209–225. <https://doi.org/10.7773/cm.v42i3.2650>.
- Montero-Serra, I., Garrabou, J., Doak, D.F., Figuerola, L., Hereu, B., Ledoux, J.B., Linares, C., 2017. Accounting for Life-history strategies and timescales in marine restoration. *Conserv. Lett.* <https://doi.org/10.1111/conl.12341>.
- Montoya-Maya, P.H., Smit, K.P., Burt, A.J., Frias-Torres, S., 2016. Large-scale coral reef restoration could assist natural recovery in Seychelles, Indian Ocean. *Nat. Conserv.* 16, 117. <https://doi.org/10.3897/natureconservation.16.8604>.
- Muñiz-Anguiano, D., Verduzco-Zapata, M., Liñán-Cabello, M.A., 2017. Factors associated with response *Pocillopora* spp. (Anthozoa: Scleractinia) during a restoration process on the Mexican Pacific coast. *Rev. Biol. Mar. Oceanogr.* 52 (2), 299–310. <https://doi.org/10.4067/S0718-19572017000200009>.
- Nava, H., Figueroa-Camacho, A.G., 2017. Rehabilitation of damaged reefs: Outcome of the use of recently broken coral fragments and healed coral fragments of pocilloporid corals on rocky boulders. *Mar. Ecol.* 38, 1–10. <https://doi.org/10.1111/maec.12456>.
- Norzagaray-López, C.O., Calderon-Aguilera, L.E., Hernández-Ayón, J.M., Reyes-Bonilla, H., Carricart-Ganivet, J.P., Cabral-Tena, R.A., Balart, E.F., 2014. Low calcification rates and calcium carbonate production in *Porites panamensis* at its northernmost geographic distribution. *Mar. Ecol.* <https://doi.org/10.1111/maec.12227>.
- Omori, M., Aota, T., Watanuki, A., Taniguchi, H., 2003. Development of coral reef restoration method by mass culture, transportation and settlement of coral larvae. In: *Toward the Desirable Future of Coral Reefs in Palau and Western Pacific*, Proceedings. Palau Int. Coral Reef Center Publication, pp. 31–38.
- Palacios-Hernández, E., Carrillo, L.E., Filonov, A., Brito-Castillo, L., Cabrera-Ramos, C.E., 2010. Seasonality and anomalies of surface temperature off the coast of Nayarit, Mexico. *Ocean. Dyn.* 60, 81–91. <https://doi.org/10.1007/s10236-009-0244-z>.
- Pandolfi, J.M., Connolly, S.R., Marshall, D.J., Cohen, A.L., 2011. Projecting coral reef futures under global warming and ocean acidification. *Science* 333, 418–422. <https://doi.org/10.1126/science.1204794>.
- Pantoja, D.A., Marinone, S.G., Parés-Sierra, A., Gómez-Valdivia, F., 2012. Numerical modeling of seasonal and mesoscale hydrography and circulation in the Mexican Central Pacific. *Ciencias Marinas* 38, 363–379. <https://doi.org/10.7773/cm.v38i2.2007>.
- Paz-García, D., Aldana-Moreno, A., Cabral-Tena, R.A., García de León, F.J., Hellberg, M.E., Balart, E.F., 2015. Morphological variation and different branch modularity across contrasting flow conditions in dominant *Pocillopora* reef-building corals. *Oecologia* 178, 207–218. <https://doi.org/10.1007/s00442-014-3199-9>.
- Perry, C.T., Spencer, T., Kench, P., 2008. Carbonate budgets and reef production states: a geomorphic perspective on the ecological phase-shift concept. *Coral Reefs* 27, 853–866. <https://doi.org/10.1007/s00338-008-0418-z>.
- Precht, W.F., Aronson, R.B., Swanson, D.W., 2002. Improving scientific decision making in the restoration of ship-grounding sites on coral reefs. *Bull. Mar. Sci.* 69, 1001–1012.
- Reyes-Bonilla, H., Carriquiry, J.D., Morales, G.E., Cupul-Magaña, A.L., 2002. Effects of the 1997–99 El Niño and anti-El Niño events on coral communities of the Pacific coast of México. *Coral Reefs* 21, 368–372. <https://doi.org/10.1007/s00338-002-0255-4>.
- Rinkevich, B., 2000. Steps towards evaluation of coral reef restoration by using small branches fragments. *Mar. Biol.* 136, 807–812. <https://doi.org/10.1007/s002270000293>.
- Rinkevich, B., 2005. Conservation of coral reef through active restoration measures: recent approaches and last decade progress. *Environ. Sci. Technol.* 39, 4333–4342. <https://doi.org/10.1021/es0482583>.
- Rinkevich, B., 2008. Management of coral reefs: we have gone wrong when neglecting active reef restoration. *Mar. Poll. Bull.* 56, 1821–1824. <https://doi.org/10.1016/j.marpolbul.2008.08.014>.
- Rinkevich, B., 2014. Rebuilding coral reefs: does active reef restoration lead to sustainable reefs? *Curr. Opin. Environ. Sustain.* 7, 28–36. <https://doi.org/10.1016/j.cosust.2013.11.018>.
- Rinkevich, B., Loya, Y., 1983. Short-term fate photosynthetic products in a hermatypic coral. *J. Exp. Mar. Biol. Ecol.* 73, 175–184. [https://doi.org/10.1016/0022-0981\(83\)90082-5](https://doi.org/10.1016/0022-0981(83)90082-5).
- Rodgers, K.S., Lorange, K., Richards-Doná, A., Stender, Y., Lager, C., Jokiel, P.L., 2017. Effectiveness of coral relocation as a mitigation strategy in Kaneohe Bay, Hawaii. *PeerJ* 5, e3346. <https://doi.org/10.7717/peerj.3346>.
- Rodríguez-Troncoso, A.P., Carpizo-Ituarte, E., Cupul-Magaña, A.L., 2010. Differential response to cold and warm water conditions in *Pocillopora* colonies from the Central Mexican Pacific. *J. Exp. Mar. Biol. Ecol.* 391, 57–64. <https://doi.org/10.1016/j.jembe.2010.06.006>.
- Sale, P.F., 2008. Management of coral reefs: where we have gone wrong and what we can do about it. *Mar. Pollut. Bull.* 56, 805–809. <https://doi.org/10.1016/j.marpolbul.2008.04.009>.
- Santiago-Valentín, J.D., Rodríguez-Troncoso, A.P., 2016. Reproducción, reclutamiento y conectividad en corales: procesos esenciales para el mantenimiento de las comunidades coralinas. In: *GC Tópicos sobre ciencias biológicas*. Universidad de Guadalajara México, pp. 11–32.
- Santiago-Valentín, J.D., Colley, S.B., Glynn, P.W., Cupul-Magaña, A.L., López-Pérez, R.A., Rodríguez-Zaragoza, F.A., Benítez-Villalobos, F., Bautista-Guerrero, E., Zavala-Casas, D.A., Rodríguez-Troncoso, A.P., 2018. Regional and species specific sexual reproductive patterns of three zooxanthellate scleractinian corals across the Eastern Tropical Pacific. *Mar. Ecol.* 39, e12497. <https://doi.org/10.1111/maec.12497>.
- Shaish, L., Levy, G., Gomez, E., Rinkevich, B., 2008. Fixed and suspended coral nurseries in the Philippines: establishing the first step in the “gardening concept” of reef restoration. *J. Exp. Mar. Biol. Ecol.* 358, 86–97. <https://doi.org/10.1016/j.jembe.2008.01.024>.
- Shaish, L., Levy, G., Rinkevich, B., 2010. Employing a highly fragmented, weedy coral species in reef restoration. *Ecol. Eng.* 38, 1424–1432. <https://doi.org/10.1016/j.ecoleng.2010.06.022>.
- Sheppard, C.R.C., Davy, S.K., Pilling, G.M., 2009. ISBN: 9780198566359 In: *The Biology of Coral Reefs*. Oxford University Press, pp. 333.
- Suding, K., Higgs, E., Palmer, M., Callicott, J.B., Anderson, C.B., Baker, M., Guttrich, J.J., Hondula, K.L., LaFevor, M.C., Larson, B.M.H., Randall, A., Ruhl, J.B., Schwartz, K.Z.S., 2015. Committing to ecological restoration. *Science* 348, 638–640. <https://doi.org/10.1126/science.aaa4216>.
- Tortolero-Langarica, J.J.A., Cupul-Magaña, A.L., Rodríguez-Troncoso, A.P., 2014. Restoration of a degraded coral reef using a natural remediation process: a case study from a Central Mexican Pacific National Park. *Ocean. Coast. Manage.* 96, 12–19. <https://doi.org/10.1016/j.ocecoaman.2014.04.020>.
- Tortolero-Langarica, J.J.A., Rodríguez-Troncoso, A.P., Carricart-Ganivet, J.P., Cupul-Magaña, A.L., 2017. Calcification and growth rate recovery of the reef-building *Pocillopora* species in the northeast tropical Pacific following an ENSO disturbance. *PeerJ* 5, e3191. <https://doi.org/10.7717/peerj.3191>.
- Vecsei, A., 2004. A new estimate of global reefal carbonate production including the fore-reefs. *Global Planet. Change* 43, 1–18. <https://doi.org/10.1016/j.gloplacha.2003.12>.

002.

- Vecsei, A., 2001. Fore-reef carbonate production: development of a regional census-based method and first estimates. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 145, 185–200. [https://doi.org/10.1016/S0031-0182\(01\)00371-6](https://doi.org/10.1016/S0031-0182(01)00371-6).
- Wilkinson, C., 2004. *Status of Coral Reefs of the World: 2004*, vol. 2, 301.
- Yap, H.T., Alvarez, R.M., Custodio III, H.M., Dizon, R.M., 1998. Physiological and ecological aspects of coral transplantation. *J. Exp. Mar. Biol. Ecol.* 229, 69–84. [https://doi.org/10.1016/S0022-0981\(98\)00041-0](https://doi.org/10.1016/S0022-0981(98)00041-0).

Glossary

Carbonate production: Mass of calcium carbonate produced by corals during a period span

in determined area, regular measured in $\text{kg CaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$.

Live coral cover: Ecological parameters that estimate the percentage of live coral cover of the total benthic coverage of determined area.

Corals of opportunity: Corals fragments resulted of natural fragmentation occasioned by bioerosion activity and high hydraulic energy (i.e., storms, waves and currents).

Ecological volume: Tridimensional growth of coral colonies in terms of occupied volume (cm^3) in the benthic substrata, measured at monthly and year level.

Attachment rate: Proportion of coral fragments which self-adhered to the substrate in a determined time.